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Current Status of the Multiwell Experiment

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ABSTRACT

The Multi-Well Experiment (MWX) is a research-oriented field laboratory whose objective is to develop the understanding and technology to allow economic production of the several years supply of natural gas estimated to be within the low permeability, lenticular gas sands of the Western United States. Features of MWX include: (1) three closely-spaced wells (115-215 ft, 35-66 m) for reservoir characterization, interference testing, well-to-well geophysical profiling, and placement of diagnostic instrumentation adjacent to the fracture treatment; (2) complete core taken through the formations of interest; (3) a comprehensive core analysis program; (4) an extensive logging program with conventional and experimental logs; (5) determination of in situ stresses in sands and bounding shales; (6) use of various seismic surveys and sedimentological analyses to determine lens morphology and extent; (7) use of seismic, electrical potential, and tilt diagnostic techniques for hydraulic fracture characterization; and (8) a series of stimulation experiments to address key questions. This paper presents the current MWX accomplishments resulting from the 1983 field season which featured the drilling of a third well and the first stimulation experiment.

INTRODUCTION AND BACKGROUND

For a number of years the United States government has engaged in research to enhance gas recovery from unconventional reservoirs, such as organically-rich fractured shale and discontinuous, lenticular, tight sandstones. Large quantities of natural gas are trapped in these formations, whose permeabilities are too low to permit economic recovery by conventional technology. In the western United States, the Greater Green River, Piceance, Wind River, and Uinta basins have been identified as containing significant amounts of gas in thick sections of lenticular sands. The National Petroleum Council has appraised[1] these four basins to hold 136 TCF (4 Tm^3) of maximum recoverable gas in lenticular reservoirs. This sizeable resource is now being investigated by the U.S. Department of Energy (DOE) in the Piceance basin of western Colorado, where a field laboratory containing three closely spaced wells penetrating the lenticular Mesaverde formation has been constructed. This facility, near the town of Rifle, is the site of the DOE Multi-Well Experiment (MWX), which has been developed to determine the viability of the lenticular tight sands as a gas resource.

Massive hydraulic fracturing has demonstrably increased gas production from tight reservoirs, but currently its performance in lenticular formations is unpredictable. This results from poor definition of reservoir properties, inadequate understanding of the physics controlling fracture propagation and proppant transport, limited ability to measure, describe, or evaluate the created fracture, and uncertainty as to the relationship of stimulation design variables (fluids, proppants, pumping rates) to the resulting fracture. These difficulties are compounded in the lenticular formations by the uncertainty whether multiple lenses, some remote from the wellbore, can be stimulated by a common treatment. Improved understanding, evaluation, prediction, and possible control of stimulation technology are needed for effective development of tight lenticular reservoirs.

The ultimate aim of the MWX is to determine the optimum stimulation technology for increasing the gas recovery from tight gas sand formations, specifically the tight lenticular formations of the basins of the western United States. Further discussion of the rationale, plans, objectives and activities can be found in References 2-5.

Experiments are now being conducted at the MWX site to 1) provide improved definition of the reservoirs through extensive core and log analyses, well and stress testing, and geologic and geophysical studies, and to 2) investigate the effectiveness of stimulation technology with diagnostic instrumentation and production performance testing.

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The intent of this paper is to present current accomplishments resulting from the 1983 field season (April-December 1983), which featured the drilling of a third well and the first stimulation activity at the site. This paper is an update to the last report presented in Denver, March 1983.[5,6]

CURRENT ACCOMPLISHMENTS

(1) With the drilling of a third well, a unique field laboratory for tight sands research has been established. MWX-3 was drilled during June, July, and August 1983. Unlike the previous two wells, a water-based, modified KCl polymer mud system was used over the entire hole. The system was maintained with little difficulty and no severe hole problems or sloughing were encountered. A 12-1/4 in (0.31 m) surface hole was drilled to 4,130 ft (1260 m) and 9-5/8 in (0.24 m) casing was run and cemented to the surface. An 8-3/4 in (0.22 m) hole was drilled and cored to a depth of 7474 ft (2278 m); 435 ft (133 m) of oriented core were obtained. Seven-inch (0.18 m) casing was run to the surface and cemented. A special open-hole section was drilled and cored between 7474 and 7564 ft (2278-2306 m) for open-hole stress testing; this section was drilled with a 5-7/8 in (0.15 m) bit, and 28 ft (8.5 m) of core were taken.

An overview of coring and logging activities in all three wells in relation to the Mesaverde geologic section at the site is given in Figure 1. The three wells were drilled with stiff-hole assemblies and are exceptionally straight as seen in Figure 2; relative separations are between 115 to 215 ft (35-66 m) between 4000 and 7500 ft (1220 to 2285 m). Significant gas shows were encountered throughout the section in all three wells, and mud weights from 10 to 15 lbs/gal (1.2-1.8 x 10^3 kg/m^3) were required to control the well; this overpressuring is shown in Figure 3.

(2) An unprecedented core analysis program is under way. Overall, 4100 ft (1250 m) of 4-in (0.10 m) diameter core, approximately 1135 ft (346 m) of it oriented, were cut with a recovery of better than 99%. The core was processed in a special field facility and then shipped to a core library at DOE's Grand Junction facility, where it is controlled through a computerized inventory system. Over 20 contractors and other interested organizations are involved in the core analyses.

Analyses to date have focused upon the lower half of the Mesaverde: the Corcoran-Cozzette sandstones and the paludal and coastal intervals (see Figure 1). Routine core analyses were performed on plugs taken at one-foot intervals over all the sands and their abutting rocks. Extensive special core analyses were also performed across major sands and into the abutting caprock. These analyses include dry Klinkenberg and relative permeabilities under restored reservoir conditions, CEC and capillary pressure measurements, mineralogy, and mechanical property determinations.

Some recent results include the following:

(a) Restored-state permeabilities at an estimated confining pressure of 2000 psi (14 MPa) range from 4-6 µd in the Cozzette to over 20 µd in the paludal interval. Water saturation effects would lower these by a factor of 3 to 10.

(b) Very high capillary pressures (~1000 psi, 7 MPa) are observed at low water saturations (35%). Hysteresis effects in dry core-water saturation measurements are consistent with these high pressures and are presumably due to the fine sand grains and presence of clay.

(c) Mechanical property data (triaxial compression, Brazilian tensile strength, and fracture toughness) have been completed for these lower intervals. The expected property differences are found between the marine sands and their bounding shales. However, the mudstones and siltstones abutting the nonmarine sands often have similar mechanical properties to the sands themselves.

(d) A prediction (apparently confirmed, see section 9) of N80±10°W for the azimuth of a hydraulic fracture at the MWX site was made based on consistent, three-well data from various measurements made on oriented core: strain relaxation, differential strain curve analysis (dsca), natural fractures, and sonic velocities. Good agreement was also obtained between actual in situ stress magnitudes (section 5) and those calculated from strain relaxation and dsca.

(e) The texture and mineralogy of the sandstones are fairly consistent throughout. Texturally, the blanket and coastal sands are very fine to fine sands size (62.5-250 µm); the fluvial sands are generally a little coarser grained. The clay minerals are predominantly illite, illite/montmorillonite, chlorite and kaolinite. Authigenic clays are common and found filling pore throats and pores.

(f) A complete story on organic maturation is evolving for the Mesaverde at the site. Extensive vitrinite reflectance data have been derived from carbonaceous shales, mudstones, siltstones, and coals. Gas samples have been analyzed from core and coals throughout the Mesaverde and from zones which have had production tests. The organic data to date suggest paleotemperature models for the region and indicate the most likely source of gas for each interval of the Mesaverde.

(g) Formation damage due to frac fluids has been studied on core from the paludal and Cozzette sands. Generally, there seems to be little damage resulting from 3-6 hour exposure to gels of intermediate weight, but damage gradually increases with time. In the laboratory, a prepad of methanol has been shown to avert any short-term damage.

(3) A comprehensive logging program was completed on MWX-3. The water-base mud system in MWX-3 allowed many logs to be run which were unobtainable in MWX-1 and MWX-2, notably, several resistivity logs with different depths of investigation and fracture identification logs. Rigorous log quality control standards were maintained in the field. Log quality is verified by extensive repeat logging, overlap of previous log runs, and well-to-well comparisons. The additional log data have been critical in the

development of improved log interpretation techniques, and the extensive MWX core data are being used to correlate and verify the log model results.

Several models have been developed which allow interpretation of critical reservoir parameters.[7,8] Fluid saturations calculated from nuclear, electric, and sonic log measurements reveal the variable invasion profile associated with tight gas sands. Comparison of the different saturation curves allows qualitative permeability estimates.

The availability of additional resistivity logs stimulated the development of a fracture identification model.[8] Fractured intervals are identified from overlays of fluid saturation traces. Model results are being verified by comparison with the five fracture identification logs run in MWX-3 and with core data. Future work includes more comparisons and the development of a fracture probability curve.

Core gamma and sonic logs are being used to help understand and correlate the rapid variation of rock properties (vertically and horizontally) in formations of lenticular morphology. The correlation of apparent lithology, mechanical rock property data, the core gamma log and the sonic log is much more complicated in lenticular formations than in formations of blanket morphology.

A start has been made in correlating various chemical and mineralogical core parameters to log measurements. Specifically, comparisons between chemical potassium, uranium and thorium measurements and spectral gamma log measurements and between mineralogical carbonate analysis and log-derived carbonate percentages are important. Improved clay volume estimates and grain density calculations will be the result. Special core analyses such as cation exchange capacity (CEC) measurements are correlated with logs in another effort to refine clay estimates. Differences between formation density and lithodensity tool bulk density measurements are also being investigated. Work is under way to define an improved algorithm for computing bulk density, and to refine the environmental corrections on log measurements.

(4) <u>Significant effects attributable to natural fractures have been seen in the results to date</u>. The occurrence and importance of natural fractures in the MWX reservoirs is illustrated by the orders of magnitude difference between reservoir matrix permeabilities measured from core, and the permeabilities which must be used in reservoir simulation models in order to reproduce the actual production data from MWX well tests. These different values are shown in Figure 4.

Thus, a multifaceted study of natural fractures at the MWX site and the Piceance basin has been initiated. Fractures in MWX core have been logged, catalogued, and segregated as to type, host lithology, and orientation. The fractures of importance occur as vertical calcite-filled or calcite-lined extension fractures in the sandstones and siltstones. Ninety-four percent of these fractures in the oriented core intervals are closely aligned with the present-day in situ principal compressive stress. Studies of surface fractures and preliminary data from petrographic studies of calcite twin lamellae confirm this orientation of stresses in the MWX area and suggest that the orientation has not changed appreciably since the late Cretaceous. A stress history model incorporating basin subsidence and uplift and pore pressure, temperature and strain histories is currently being developed in conjunction with the United States Geological Survey. Combined with additional studies which have defined the operable fracture mechanism, a prediction of the fracture system(s) will be available for evaluation with MWX and other basin data.

(5) <u>Additional high resolution stress tests have been made in the marine and paludal intervals</u>.[9,10] Six stress tests have been performed in the marine section above the Cozzette member and eleven tests have been conducted in the paludal interval. In addition, two open-hole stress tests were performed in MWX-3 in the Rollins member at the top of the marine section.

In the marine rocks, large stress differences exist between the blanket sandstones and the bounding shales. This is a favorable situation for hydraulic fracture containment and, thus, the creation of long penetrating fractures. In the paludal interval, the situation is not so clear due to a complex lithology of narrow, lenticular channel sands surrounded by coals, siltstones, mudstones and carbonaceous shales. No clear correlations between stress magnitudes and lithology are apparent. In some cases, sandstones have much lower stresses than the abutting materials; in other cases the stresses are nearly equal or even slightly higher in the sands. Further, a 500 psi (3.45 MPa) difference in stress in the same zone between two wells was observed. Lateral variations are probably common in this lithology.

Two open-hole stress tests were performed to determine the maximum principal in situ stress, to determine the orientation of the induced fractures and to compare the results with the stress tests conducted through perforations. These were performed at a depth of about 7500 ft (2286 m) in the Rollins sandstone and the minimum and maximum stresses were found to be about 6800 psi and 7200 psi (46.9 and 49.6 MPa) respectively. This 400 psi (2.76 MPa) stress difference may be significant for hydraulic fracture design. The orientation of the fractures was not unequivocal; it appeared to be N50°-70°W, but the observed fractures were small, en echelon, and discontinuous. The minimum stresses measured through perforations in MWX-2 and open hole in MWX-3 agreed within 175 and 10 psi (1.21 and 0.07 MPa) for tests at two comparable depths.

(6) <u>The paludal is the current interval of interest for stimulation and sedimentological characterization of it has been completed</u>. Figure 5 depicts the paludal and its five zones of interest, which lie between 6800 ft and 7450 ft (2078-2271 m) and have been characterized by sedimentological studies of core, logs and paludal outcrops.[11] Numerous coal seams increase the complexity of this interval. Four of the five targeted reservoirs (zones 1, 2, 3 and 5) in the paludal zone are interpreted to be lenticular distributary-channel sand bodies. They are probably on the order of 200 to 500 feet wide, as calculated from height-to-width

relationships of these sand bodies seen in outcrop. These lenticular reservoirs are probably oriented east-west to northeast-southwest, the main bodies passing through MWX-1 and MWX-2, but only the fringes being penetrated by MWX-3.

Zone 4 is interpreted as a large splay deposit: although it is a clean sandy zone as seen in MWX-3 core, the sedimentary structures indicate low energy deposits (ripples) rather than main-channel crossbeds. This zone in MWX-2 core is much less sandy, indicating a lateral facies change to distal muddy splay deposits. The stimulation of closely adjacent zones 3 and 4 as a unit will mingle production from a lenticular (channel) reservoir and a more circular (splay) type of reservoir.

(7) Several well tests were completed in the paludal interval. These tests included single and multiple well drawdown, buildup and interference tests in three individual sands (zones 2, 3 and 4). Previous testing and analysis of the lower marine blanket sands indicated that a substantial natural fracture network existed within these microdarcy matrix reservoirs. In addition, a large number of natural fractures were found in core in the fluvial interval. Therefore, it was not surprising that these initial paludal tests were not consistent with estimates of microdarcy permeabilities measured in core.

A single well test in MWX-1 in zone 2 was considered adequate to assess the zone's reservoir parameters, as log and core data indicated poor quality in MWX-2 and -3. A pair of drawdown and buildup tests were conducted over a one-month period. Reservoir modeling of these data required not only the inclusion of parallel reservoir boundaries defined by sedimentological interpretation, but also an orthogonal no-flow boundary passing through MWX-2. This no-flow boundary was further evidence for the existence of a high angle fault which cuts only MWX-2 at ~7050 ft (2150 m). The effect of the underlying coal seams remains uncertain. However, the data fit was exceptional and defined an average reservoir permeability almost 25 times core permeability (50 μd vs 2.3 μd). This was a significant test in several respects: (1) it clarified qualitatively that the paludal sandstone reservoirs were naturally fractured; (2) it confirmed the channel boundaries predicted from log, core and sedimentological analysis; and (3) it demonstrated that the existence of a nearby fault could be measured and modeled in a tight, naturally fractured reservoir.

Zones 3 and 4 have been selected as the target for the stimulation experiment in the paludal interval. In the absence of measured in situ stress contrasts, these would not be separated during fracturing and were thus co-mingled during well testing. An interference test was conducted with MWX-1 being produced at a constant rate of 250 Mcfd (7000 m^3/d) and MWX-2 and MWX-3 monitored with quartz-type pressure gauges and downhole shut-in tools to minimize the effects of wellbore storage. The drawdown of MWX-1 continued for seven days and monitoring of all three wells was continued for four days following shut-in; the tests could not be continued due to constraints on winter operations. No interference was detected in either offset well. This was different than the hour's response noted in the Cozzette,[5] and is undoubtedly due to the complexity of these two paludal zones.

(8) The first stimulation experiment is being conducted in the paludal interval at a depth of 7070-7150 ft (2155-2179 m). The experiment is divided into two parts: Phase 1 includes step-rate and flow-back tests and two minifracs which were conducted in December 1983, and Phase 2 is a complete stimulation to be conducted in Spring 1984.

The Phase 1 tests were conducted in MWX-1 and consisted of: (1) step-rate tests at 10 rates between 0.2 and 8 bbl/min (0.03 and 1.3 m^3/min); (2) flow-back tests at 1.0 and 1.3 bbl/min (0.16 and 0.20 m^3/min); (3) a 15,000 gal (57 m^3) minifrac with 30 lb/1000 gal (3.6 kg/m^3) gel; and (4) a 30,000 gal (114 m^3) minifrac with 60 lb/1000 gal (7.2 kg/m^3) gel. Both minifracs were pumped at 10 bbl/min (1.6 m^3/min) and no proppant was used. The primary objective of Phase 1 was to determine fracture behavior and geometry as propagation progressed through and out of the sand lenses. This was accomplished by monitoring fracture growth with borehole seismic packages[12] in the two offset wells, by analyzing the pressure decline after shut-in after the two minifracs,[13] by post-frac temperature surveys, and by analyzing treatment pressures.[14]

The step-rate/flow-back tests yielded an estimated minimum in situ stress of about 5900 psi (40.7 MPa), which was about 100 psi (0.7 MPa) greater than measured previously in MWX-3. The fracture parameters resulting from the two minifracs are shown in Table I. Fracture pressures indicate fracture length extension without significant height growth (except possibly at the very end of the second treatment). Apparently this zone has containment features and can probably support a relatively large fracture treatment. Phase 2 will utilize this design information as well as stress, geologic, core and reservoir data. It will be a sand-propped fracture and will feature both borehole seismic and surface electrical potential fracture diagnostics[15] and a post-frac well testing program involving all three wells.

(9) Borehole seismic fracture diagnostics measured fracture azimuth and limited fracture height growth during the Phase 1 minifracs.[12] Three-axis borehole seismic systems were positioned slightly above zones 3 and 4 in the two offset wells during the Phase 1 tests. The packages were oriented by perforation shots in the two zones in MWX-1. (After orientation, additional perforations could be located within 1-5 ft (0.3-1.5 m).) Noise in MWX-2 due to gas leakage through poorly-squeezed perforations prevented source location by triangulation, the preferred method. A small percentage (5%-10%) of the events could be analyzed by p- and s-wave arrival times using the three-axis data from MWX-3 alone. The source locations in plan view and as projected on the plane of this azimuth are shown in Figure 6. The best-fit azimuth is N66.6±8.0°W, in good agreement with earlier predictions (see section 2). Fracture height is consistent with the post-frac temperature surveys and frac analyses.

CONCLUSION

The Multi-Well Experiment is a unique research-oriented field laboratory whose range of activities will answer key questions about the variability of, and production from, the lenticular, tight gas sand resource. The laboratory has been completed with the drilling and characterization of a third well. Significant accomplishments have been documented and the first stimulation experiment is under way. Several years of stimulation and testing throughout the Mesaverde are planned at levels dictated by future funding decisions.

ACKNOWLEDGMENTS

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TABLE I.

Fracture Parameters from the Phase 1 Minifracs*

	Minifrac #1	Minifrac #2
Size, gal (m^3)	15,000 (57)	30,000 (114)
Wing length, ft (m)	240 (73)	440 (134)
Height, ft (m)	135 (41)	150 (46)
Width at wellbore, in (cm)	0.46 (1.2)	0.62 (1.6)
Leakoff coefficient, ft/√min (m/√min)	0.00129 (0.0004)	0.0007 (0.0002)

*Height from post-frac temperature survey; other parameters from the shut-in analysis in Reference 13.

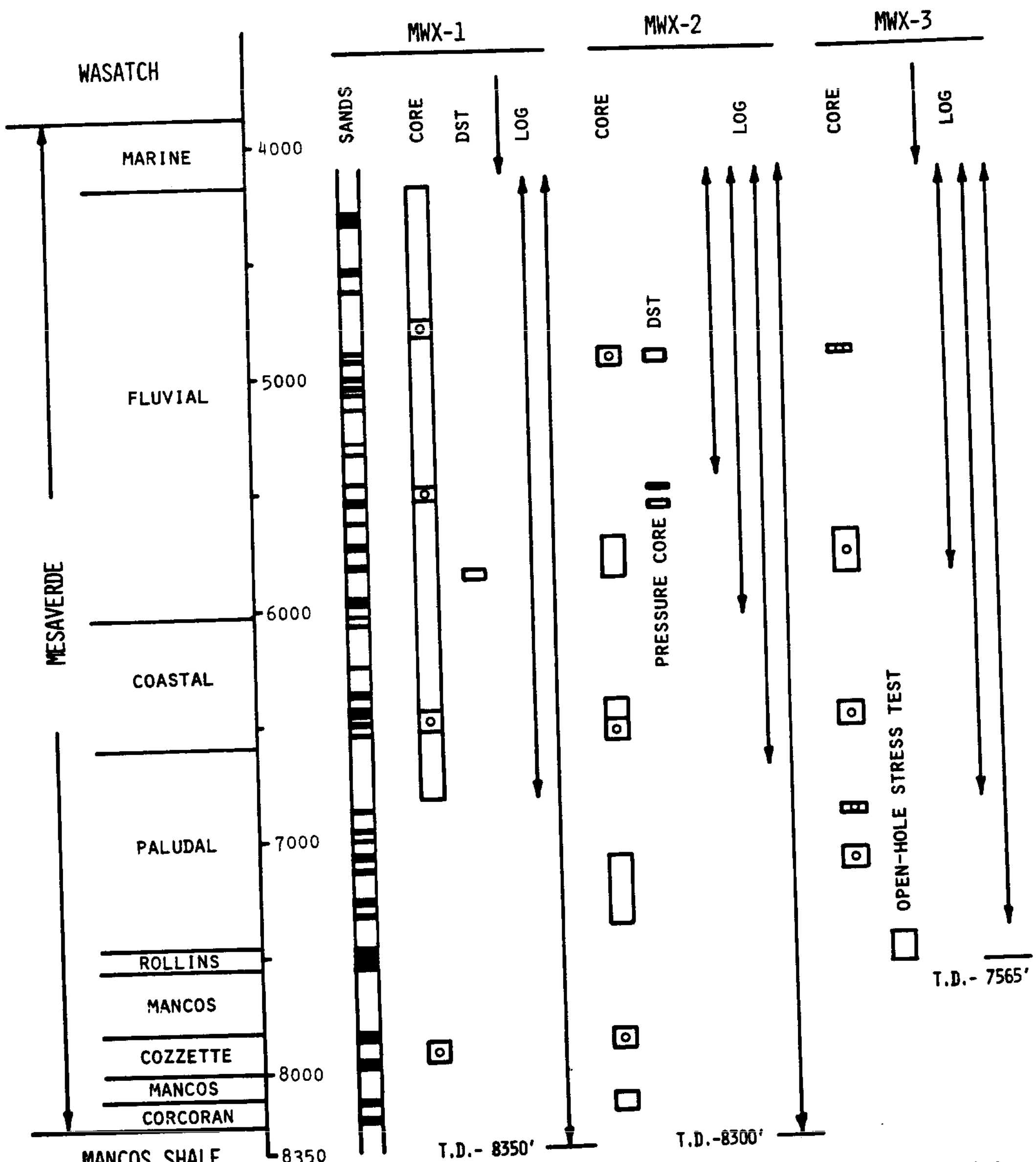

Fig. 1—Summary of Mesaverde geology and core and log intervals for the three wells at the MWX site.

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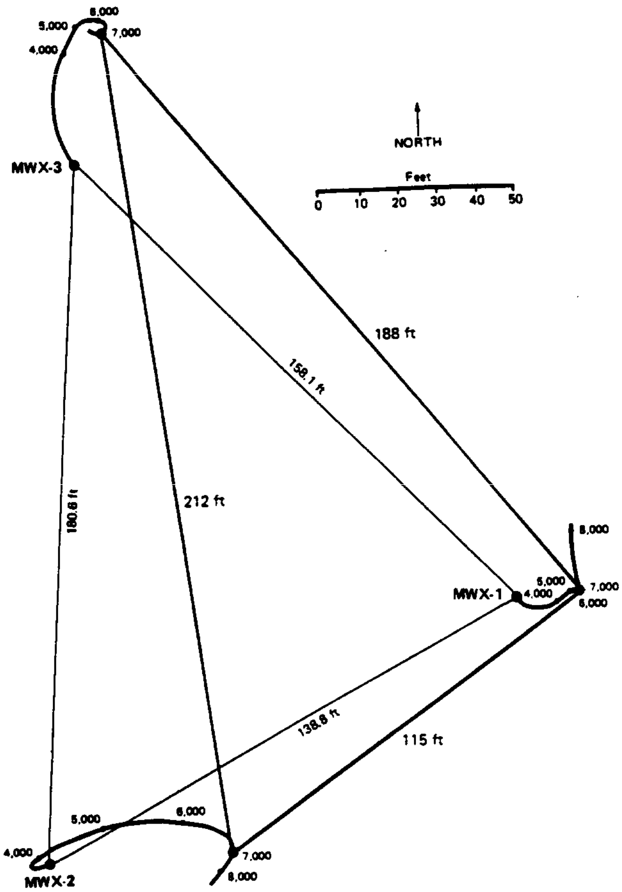

Fig. 2—MWX well surveys and relative separations.

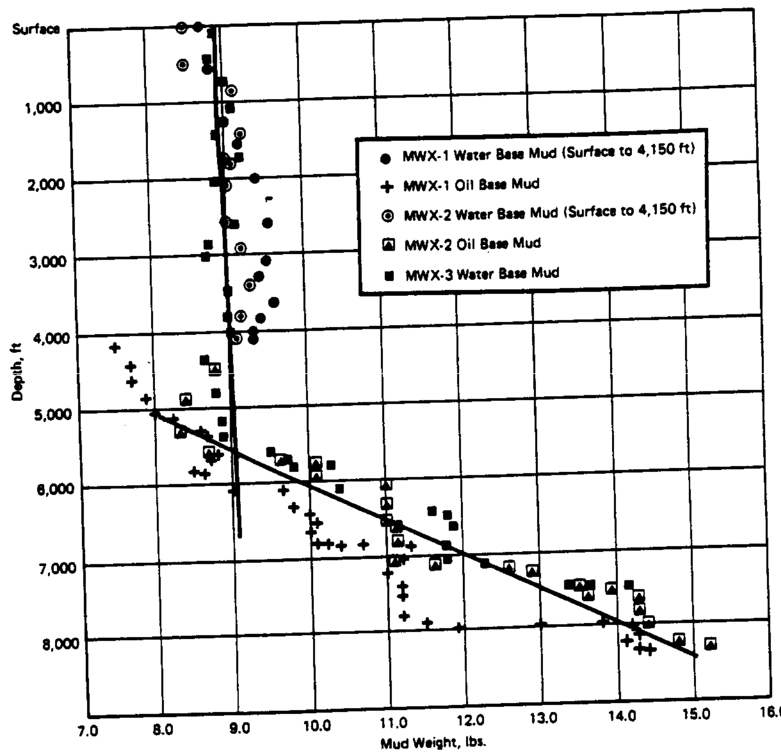

Fig. 3—Mud weight vs. depth.

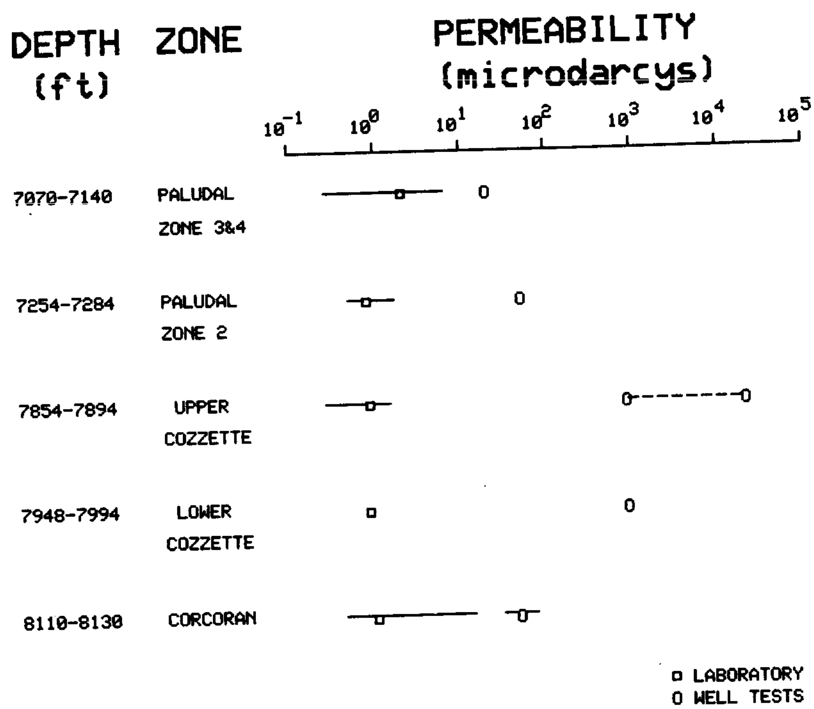

Fig. 4—Core and well test permeabilities.

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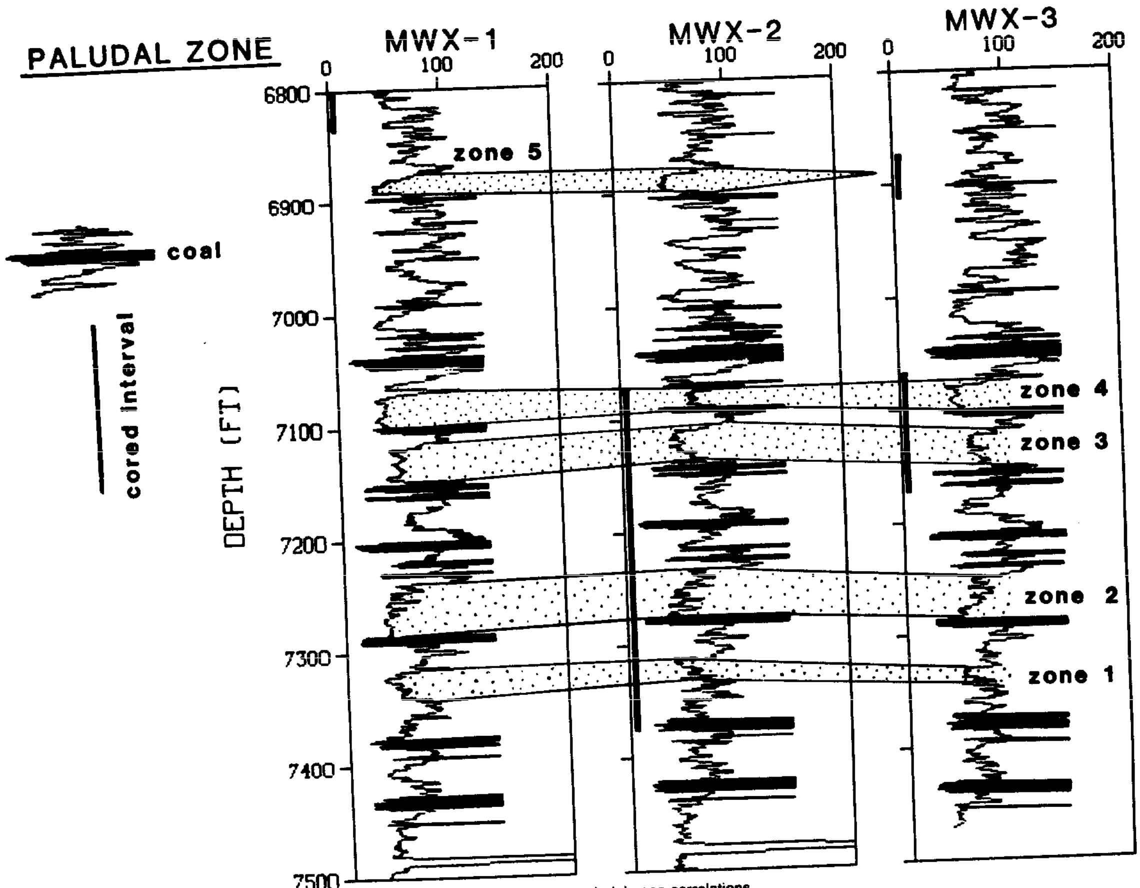

Fig. 5—MWX paludal zone correlations.

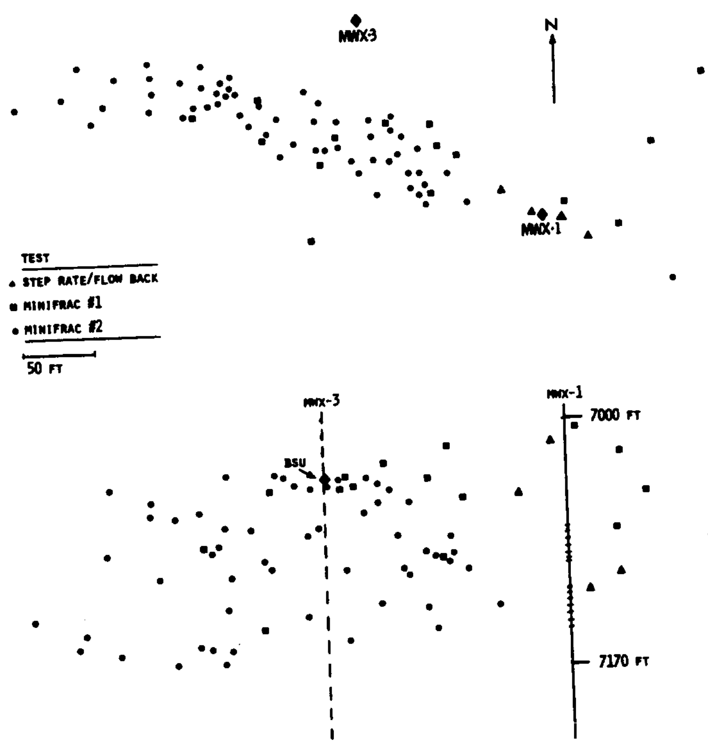

Fig. 6—Seismic source locations.[12] Top: plan view indicating hydraulic fracture azimuth. Bottom: side view; locations as projected onto azimuth plane.

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